INVESTIGATION OF THE FEASIBILITY OF SECONDARY RECOVERY OF GROUND WATER FROM THE OGALLALA AQUIFER

A Report To The Sixty-Eighth Legislature

THE STATE OF TEXAS

LP-185

TEXAS DEPARTMENT OF WATER RESOURCES

NOVEMBER 1982

INVESTIGATION OF THE FEASIBILITY OF SECONDARY RECOVERY OF GROUND WATER FROM THE OGALLALA AQUIFER

A Report To The Sixty-Eighth Legislature

Based on a study completed under contract with the
High Plains Underground Water Conservation District No. 1

LP-185

Texas Department of Water Resources

November 1982

Published and distributed
by the
Texas Department of Water Resources
Post Office Box 13087
Austin, Texas 78711

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Transmitted herewith is a report which the Department was directed to prepare for the Sixty-eighth Legislature by November 30, 1982. The report presents the Department's assessment of an investigation of the feasibility of secondary recovery of ground water from the Ogallala aquifer, which it was charged with making by the Sixty-seventh Legislature.

It appears that the injection of air into the unsaturated zone of the aquifer offers, in some locations, exciting possibilities of increasing the volume of water recoverable from the aquifer. The Department will be pleased to supplement the material presented herein at the request of any interested reader.

Respectfully submitted,

Harvey Davis

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Executive Director

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TABLE OF CONTENTS

page

SUMMARY OF RESULTS, CONCLUSIONS, AND RECOMMENDATIONS.................. 1

INTRODUCTION.. 6

- Project Goal and Objectives.. 6
- Project Organization.. 7
- Study Period.. 9
- Study Area.. 10
- The Ogallala Formation – Aquifer.................................... 10

OCCURRENCE AND AMOUNT OF WATER IN CAPILLARY STORAGE.................. 13

LITERATURE REVIEW... 19

LABORATORY STUDIES AND MATHEMATICAL MODELS............................ 21

- Laboratory Studies.. 21
- Mathematical Models... 23

THEORY OF AIR INJECTION INTO THE UNSATURATED ZONE..................... 25

FIELD-TEST PROGRAMS... 32

- Slaton Air-Injection Test One....................................... 32
- Slaton Air-Injection Test Two....................................... 38
- Idalou Field Program.. 41

ECONOMIC ANALYSIS... 51

REFERENCES.. 55

STUDY TEAM PERSONNEL.. 56

ACKNOWLEDGEMENTS.. 58

page

FIGURES

1. Map Showing Location and Extent of the High Plains Aquifer in Texas.......... 11

2. Conceptual Illustration of Capillary Water Held in Storage.......... 14

3. Conceptual Illustration of Water Held in Storage Under Saturated Conditions.......... 16

4. Conceptual Illustration of Effects of Drainage on Water Held in Storage.......... 26

5. Diagram of Idealized Capillary Water Conditions.......... 28

6. Conceptual Illustration of Air Injection Theory.......... 31

7. Map Showing Locations of Field Program Sites.......... 33

8. Photograph of Idalou Field Test Site, Showing Air-Injection Well, Air-Monitoring Equipment, and Air Compressor.......... 43

9. Photograph of Pressure Tank Containing Continuous Water-Level Recorder.......... 44

page

10. Photographs Showing Field Test Monitoring Techniques............. 45

11. Photograph of Water Forced to Surface During Idalou Field Test.... 47

INVESTIGATION OF THE FEASIBILITY OF SECONDARY RECOVERY OF GROUND WATER FROM THE OGALLALA AQUIFER

A Report To The Sixty-Eighth Legislature

SUMMARY OF RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

The Texas Department of Water Resources was authorized by the Sixty-seventh Legislature to investigate the feasibility of secondary recovery of ground water from the Ogallala aquifer. Following is a summary of the Department's assessment of the investigation presenting results and conclusions by project objective, and a list of major recommendations.

Objective 1: Determine the Amount of Water in Capillary Storage.

Test hole drilling and core analysis work showed that the moisture content for material between the bottom of the root zone (about 10 feet below land surface) and the 1980 water table ranged from 10 to 40 percent by volume with an average of about 25 percent. Using the average value, the 3.35 billion acre-feet of currently unsaturated material in the Ogallala Formation in the High Plains of Texas would contain about 840 million acre-feet of capillary water. The amount of capillary water which may remain when the currently saturated portion of the formation (some 2.5 billion acre-feet of material) is drained equals about 625 million acre-feet, for a total potential of 1.46 billion acre-feet of capillary water. Not all of the area is probably suitable for recovery techniques and not all of the capillary water can be recovered.

This work indicates that significant volumes of capillary water are in storage. If only a small portion of this water could be recovered, the amount of water available on the High Plains would be significantly increased.

Objective 2: Identify Available or Emerging Technologies for Recovery of Capillary Water.

An exhaustive review of existing literature was carried out in an attempt to identify available or emerging technologies for secondary recovery of capillary water. No articles pertaining directly to secondary recovery of ground water were located. Early articles pertaining to secondary recovery of petroleum were researched, but few applied to recovery from material similar to the Ogallala. Five potential secondary recovery techniques were identified: air drive, surfactant/foam, thermal, vibration, and electro-osmosis. Preliminary analysis indicated that air drive and surfactant/foam were the most feasible techniques for ground-water application.

Objective 3: Evaluate Capillary Water Recovery Techniques.

The identified techniques were studied by means of laboratory experiments and analytical calculations. Laboratory tests showed that applying 2 pounds per square inch (psi) air-drive pressure resulted in a 20 percent increase in water yield over that obtainable by gravity drainage alone. It was also determined that the air-injection zone must be capped with a confining layer to restrict loss of air and pressure. The addition of surfactants to a sand column increased water drainage by over 25 percent. Rapid adsorption of surfactants by soil particles, however, resulted in the estimated cost of surfactants for this type of recovery system being at least $3,000 per acre-foot of recovered water. Research on the vibration, thermal, and electro-osmosis techniques showed that they would be very energy intensive.

The laboratory tests showed that an air-drive system can release capillary water from storage. The other four identified techniques were judged to be too expensive to be economically feasible.

Objective 4: Develop Plans to Field Test a Recovery Technique.

Plans for three field programs were prepared. The first two of the programs were primarily tests of field procedures rather than of recovery technologies. Plans developed included site selection parameters, well construction techniques, and measurement/monitoring procedures. An air-injection site for secondary recovery of ground water should have a confining layer above the target injection zone that greatly hinders air flow. Saturated clay layers worked well in providing this confinement but they caused well construction problems. Well designs developed appear to be non-site specific, with wrapped well screen being the type best suited for injecting air. The original design of air-monitoring wells was good, and plans for water-level measuring and soil-moisture monitoring wells evolved during the study.

The plans for field tests were deemed adequate to allow a major field test to be conducted.

Objective 5: Field Test a Secondary Recovery Technique.

A large-scale field test of air drive for secondary recovery of capillary water was conducted near Idalou, Texas. Over 10 million cubic feet of air was injected over a 6-day period. Injection rates were as high as 2,300 cfm with pressures as high as 160 psi. Results showed that an area of over 140 acres was pressurized. In one area, the soil-moisture content decreased, an expected result of increased recovery. Water levels in wells around the injection site rose, and the area around the test site contained an estimated additional 225 acre-feet of water available to wells 1 month after the test. An economic analysis showed that if the additional water was available due to air injection, it would cost $84 per acre-foot. Water at this cost could currently be used profitably by a cotton farmer if very favorable conditions existed. A city could likely afford to pay up to $136 per acre-foot presently for ground water.

It is concluded that after injection of air during the field program at Idalou, the saturated portion of the aquifer contained additional water which could be pumped by conventional wells. However, the reason for the extra water is not fully understood. The cost of such recovery probably is economically feasible only for municipalities whose existing water supply is almost exhausted. Sites with a saturated clay layer overlying the injection zone appear to offer good prospects of secondary recovery by air injection.

Recommendations:

1. The exact nature of the processes causing capillary water to be released needs to be better understood. These processes and the manner of movement of the freed capillary water should be defined so that the whole process can be mathematically modeled. Models

developed in this study could be the foundation for the expanded modeling. Data collected during this study should be more completely analyzed.

2. Refined field test monitoring procedures should be developed. The procedures should be automated as much as possible and should provide for the continuous collection of data.

3. After recommendations 1 and 2 have been accomplished, field demonstrations of the recovery technique selected should be conducted in other areas of the High Plains and monitored closely. Within 1 mile of the demonstration sites, no wells should be pumped for at least 6 months prior to air injection. The sites should be monitored for at least 6 months after injection ends and nearby wells should not be pumped during this period.

INTRODUCTION

The Sixty-seventh Texas Legislature authorized the Texas Department of Water Resources to investigate the feasibility of secondary recovery of ground water from the Ogallala aquifer and appropriated funds to the Department for the investigation. The Legislature's action was in response to a request from the High Plains Underground Water Conservation District No. 1 that such an investigation be made. The investigation was conducted as a cooperative effort between the Department and the District. The District, in turn, was assisted by Texas Tech University and the Texas A&M Agricultural Experiment Station at Lubbock. This report is the Department's assessment of the investigation. It is based largely on the Draft Project Report submitted by the District in compliance with its contract with the Department.

Project Goal and Objectives

The goal of the investigation was to determine whether sufficient quantities of capillary water are stored in the Ogallala Formation above the present water table to warrant efforts to recover the water and, if sufficiently large amounts are found, to develop economically feasible mechanisms for releasing the water. Early in the study, the following three key definitions were developed:

> Capillary water is that water in the zone between the water table and the land surface that is held between soil particles by molecular attraction and capillarity. [During the study, the term was used to refer to all water held above the water table by whatever means.]

A capillary water recovery technique is technically feasible if its application would result in a significant increase in the volume of water available for pumping from conventional wells.

A capillary water recovery technique is economically feasible if the unit cost of making the additional water available is approximately equal to the direct benefits derived from having a needed unit of water available for agricultural use and for municipal and industrial use.

Based on the Legislature's charge to the Department, five study objectives were established:

1. Determine the amount of capillary water in storage,

2. Identify available or emerging technologies for recovery of capillary water,

3. Evaluate capillary water recovery techniques with respect to their technical and economic feasibility,

4. Develop plans for conducting pilot field programs to test one or more of the capillary water recovery techniques, and

5. Conduct a field test to verify technologic and economic feasibility of one or more capillary water recovery techniques.

Project Organization

The organization assembled to perform this study involved a multidisciplinary team of engineers, geologists, scientists, economists, other professionals, technicians, and support personnel. A listing of many of the key personnel who contributed significantly to the study may be found at the end of this report.

The Texas Department of Water Resources served as project sponsor. The Department provided a portion of the study funding, construction of the test holes, and general assistance to and supervision of the project.

The High Plains Underground Water Conservation District No. 1 contracted with the Department to perform the study and was responsible for overall study activities including the execution of field tests. The District also contributed funds to the study.

The Water Resources Center at Texas Tech University contracted with the District to assist in conducting the study. University efforts included laboratory tests, literature research, and analytical studies.

The Texas A&M Agricultural Experiment Station at Lubbock provided laboratory analysis of soil samples.

The District retained the services of recognized experts to serve as an Advisory Board. The purpose of this Board was to advise the District on capillary water recovery techniques, procedures for evaluating the pilot test, and any other topics related to the study. The Board was comprised of the following five members:

Charles Wendt, PhD, Soil Physicist, Texas A&M University System, Texas Agricultural Experiment Station, Lubbock, Texas (Dr. Wendt served as chairman of the Board.)

Warren W. Wood, PhD, Ground-Water Hydrologist, Research Scientist, U.S. Geological Survey, Reston, Virginia

Ron Lacewell, PhD, Economist, Agricultural Economics Department, Texas A&M University, College Station, Texas

Ron M. Brimhall, P.E., Petroleum Engineer, Petroleum Engineering Department, Texas A&M University, College Station, Texas

Terry Doherty, Ground-Water Physicist, Pacific Northwest Laboratories, Battelle, Richland, Washington

Study Period

The District and the University began work on secondary recovery techniques during the summer of 1981. The actual study began on September 1, 1981, and was to be completed with submittal of a report to the Texas Legislature by November 30, 1982.

Major milestones of the project were:

October 21 and 22, 1981	First Meeting of Advisory Board
November 20, 1981	Second Meeting of Advisory Board

January 23 through February 1, 1982	First Field Test at Slaton
April 8 and 9, 1982	Third Meeting of Advisory Board
May 28 through June 1, 1982	Second Field Test at Slaton
June 17 through June 23, 1982	Field Test at Idalou
September 23, 1982	Submittal of the District's Draft Project Report to the Department
November 2 and 3, 1982	Final Meeting of Advisory Board

Study Area

The study area is that portion of the High Plains of Texas that is underlain by the Ogallala aquifer (High Plains aquifer). The Texas portion of the Ogallala aquifer occupies an area of about 35,000 square miles and underlies parts or all of 46 counties (Figure 1). This area accounts for nearly 70 percent of the total irrigated acreage in the State and produces over 20 percent of the food and fiber grown in the United States. Agricultural production in the area is directly related to obtaining irrigation water from the Ogallala aquifer.

The Ogallala Formation - Aquifer

The Ogallala Formation is a system of complexly interbedded sand, silt, clay, and gravel which underlies the Great Plains and extends into the Texas Panhandle. The Ogallala aquifer, the major water-bearing unit of the Great Plains, is that part of the Ogallala Formation which is completely saturated with water. This study, however, was concerned with the water within the formation, but above the water table and, therefore, technically not within

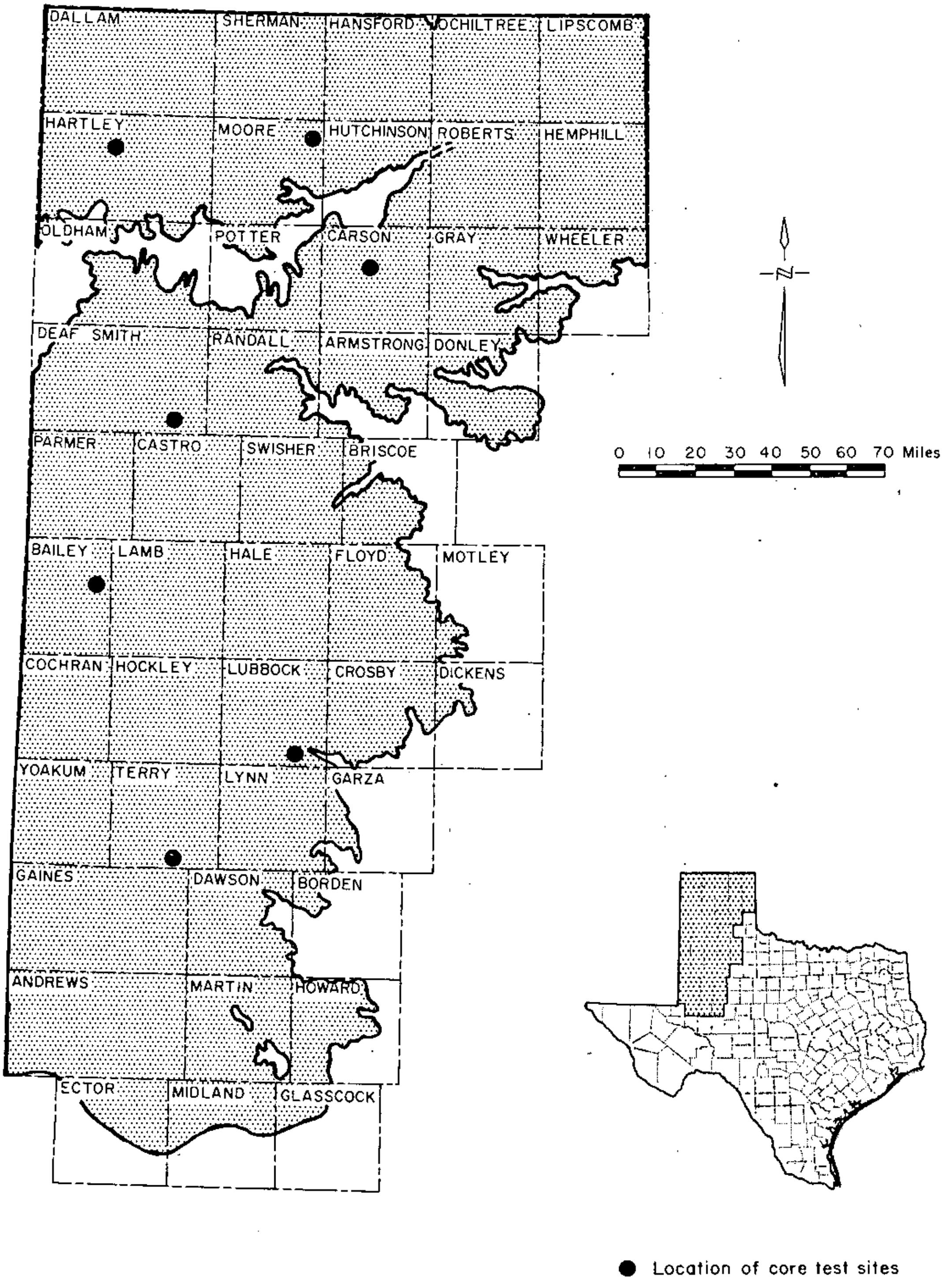


Figure 1

Location and Extent of the High Plains Aquifer in Texas the Ogallala aquifer.

The Ogallala Formation is made up of rock materials washed from the Rocky Mountains during an extended time of heavy rainfall. These sediments first filled existing stream valleys, and then these deposits gradually grew together to form a broad alluvial apron stretching from Texas to the Dakotas. Flow within the mountain-source areas was very fast, allowing the streams to transport vast amounts of rock material. On the flat prairie the water slowed down, dumping much of its load of sediment. On the flats, the rivers meandered back and forth depositing the material and then reworking it again and again. All of this deposition, erosion, and re-deposition has added to the complexity of bedding within the Ogallala. After the deposits had reached thicknesses of up to several hundred feet and covered an area well beyond their present extent, rainfall and stream deposition began to diminish, and erosion eventually cut off the Ogallala from its source area to the west. In addition, the areal extent of the formation was reduced. The shallow calcium carbonate-cemented beds which occur at or near the surface over much of the Ogallala have slowed the erosion process and protected underlying strata from removal.

Within the Ogallala Formation, thick elongated channel deposits, often of coarse sand and gravel, follow the meandering courses of the ancient rivers; while above, below, and alongside are thin flat-lying beds of sand, silt, clay, and gravel sorted or graded by the flood flows. In a regional sense, the sand beds within the formation exhibit enough interconnection for the entire sequence to act as an aquifer where saturated. Locally, however, silt and clay beds may retard vertical movement of water enough to form perched water tables or artesian conditions.

OCCURRENCE AND AMOUNT OF WATER IN CAPILLARY STORAGE

The first objective of the study was to determine the amount of capillary water in storage.

A formation, such as the Ogallala, is composed of the three states of matter: solid, liquid, and gas. The solid material is the sand, silt, clay, and gravel. These materials range in size from very small to large and are in many different shapes. The size, shape, and degree of sorting of the solid particles govern how the solid material is packed together. The solid material does not completely fill a given volume; space exists between the particles. These spaces are called voids, and they may be filled with water or air.

For almost all naturally occurring formations, the solid material, such as a sand grain, is slightly wet. A very thin layer of water, a few molecules thick, surrounds the sand grain. This water is held to the sand grain by atomic forces, and about the only way to remove this layer of water is to cook the sand grain in a very hot oven. This is not the water of interest in the study.

If the formation is wetter than described above, additional water is held between the sand grains. This water is held in narrow sections of the voids (Figure 2). This is the capillary water that was the subject of the investigation. Water would drain from even the narrowest voids due to gravity if it were not for the phenomenon of surface tension. Surface tension occurs in any water surface, but is so weak that it becomes important only when the surface area is quite small. Surface tension keeps the water between the sand grains.

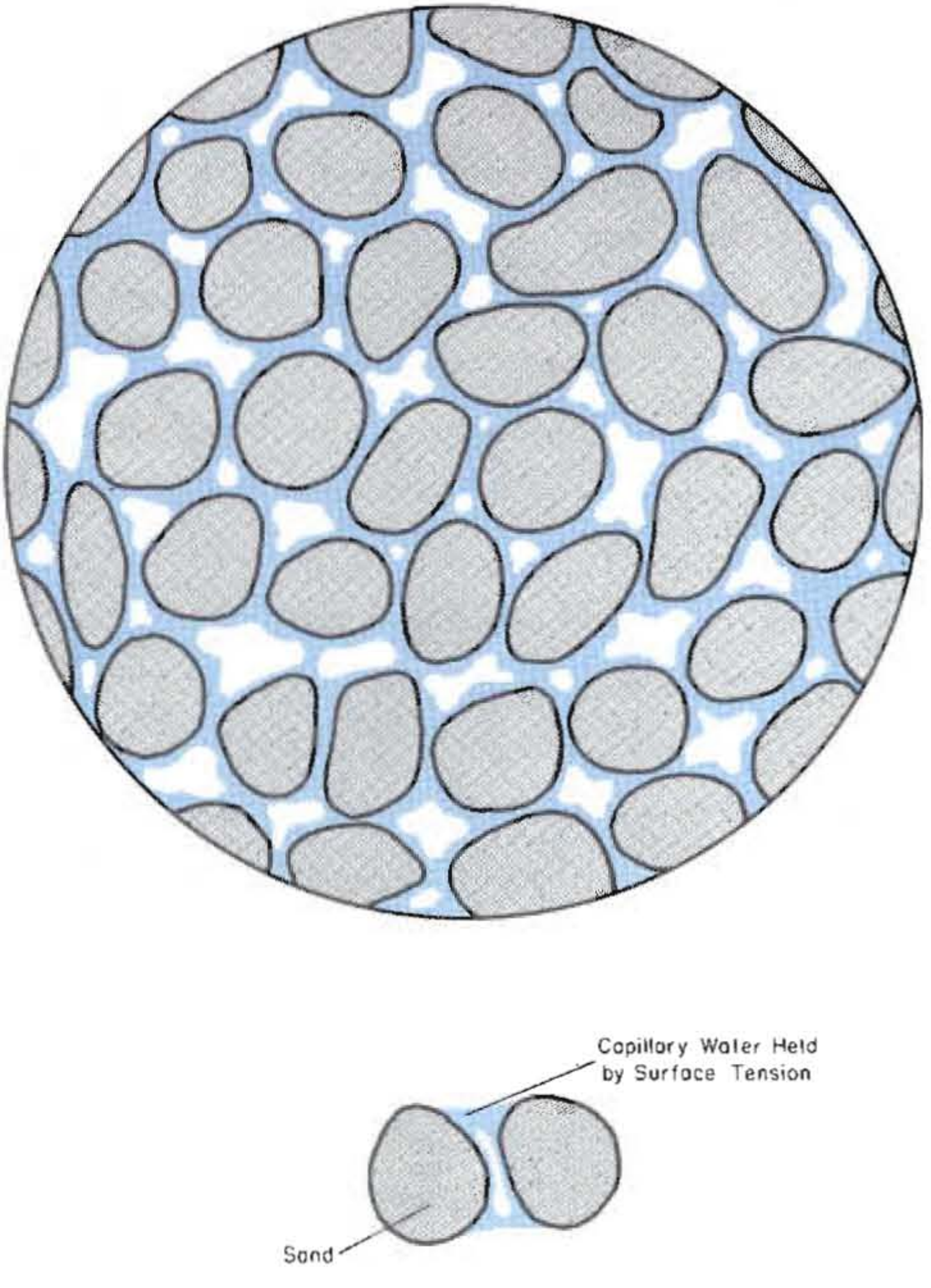


Figure 2
Conceptual Illustration of Capillary Water Held in Storage

As the formation becomes wetter, some of the voids are completely filled with water. An area containing completely full voids may be surrounded by voids that contain only capillary water.

The three above described conditions are unsaturated because not all of the voids are filled with water. If the voids are completely filled with water, the formation becomes saturated (Figure 3). In the larger voids, much of the water that is in storage will drain from the void due to gravity. This is the water that flows to a well and is pumped to the surface. This water, referred to as gravity water in Figure 3, is what is normally referred to as ground water, and it will be referred to as such in this report. The top of this saturated portion is called the water table.

Two major activities were completed to meet the first objective. First, a drilling program was conducted to obtain data describing the moisture content of the material above the water table. Most, if not all, previous studies of the Ogallala were directed at the saturated portion of the aquifer, but this drilling effort was aimed at the unsaturated portion, that portion above the water table.

Initially, seven drilling sites were selected by the District based on the geology of the Ogallala. The sites were selected so that data obtained from the sites could be used to estimate moisture conditions across the High Plains. These sites, plus others, were drilled with the Department's drilling rig, and great care was taken to ensure that the formation samples obtained from the holes remained, as nearly as possible, in their natural condition. The test holes totaling over 2,500 feet of drilling, were located in Bailey, Carson, Deaf Smith, Hartley, Lubbock, and Terry Counties.

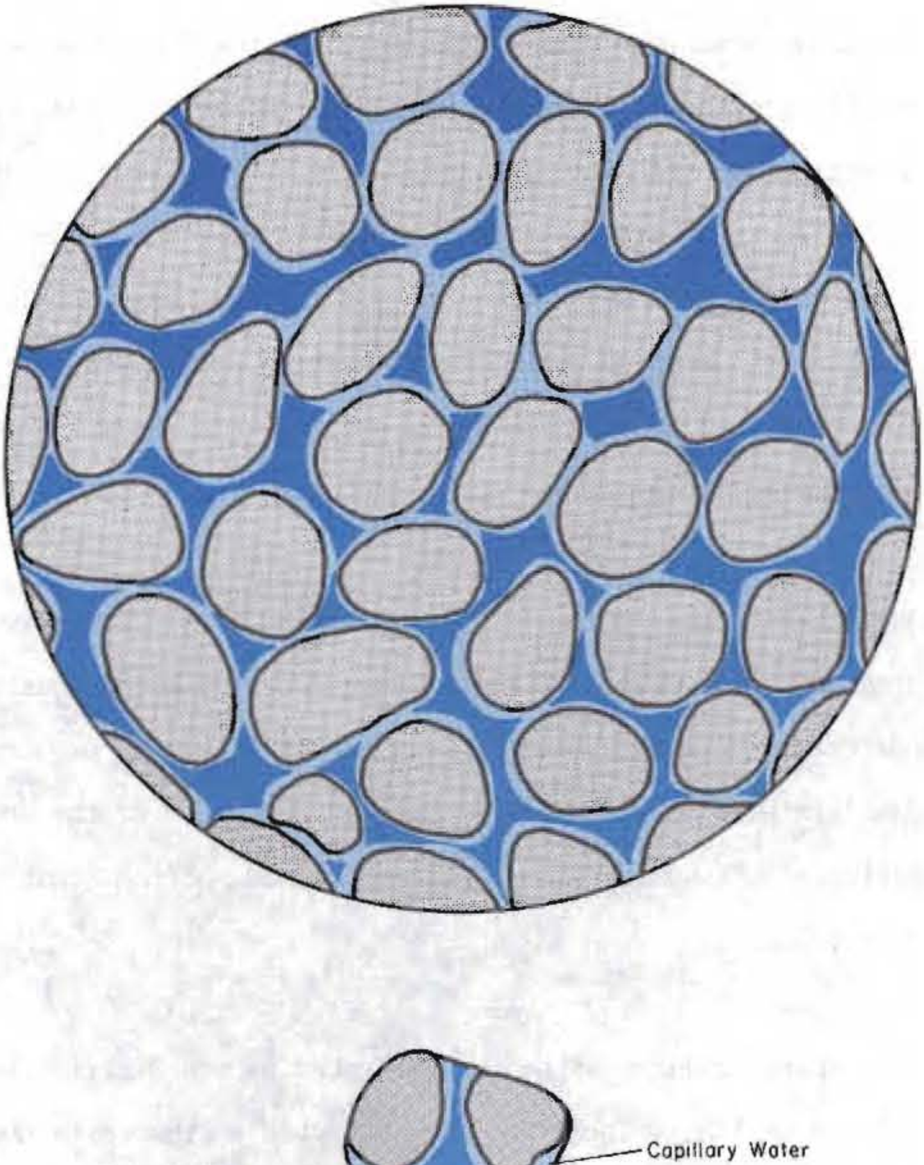


Figure 3
Conceptual Illustration of Water Held in Storage Under Saturated Conditions

The formation samples were tested by the Department's Materials Testing Laboratory and by Texas Tech University. The samples were analyzed for several parameters, the primary one being percent moisture by volume. The percent moisture ranged from less than 10 to more than 40 percent. The average value for all samples tested by the two laboratories was 25.9 percent. For gross estimation of the percent moisture in the unsaturated zone across the High Plains, a value of 25 percent is assumed reasonable.

The second activity was to determine the volume of material that contains capillary water. Maps were constructed to show the distance separating the water table in 1980 and the bottom of the vegetation root zone (assumed to be 10 feet below land surface). Using these maps, the volume of that portion of the formation containing capillary water was calculated to equal 3.35 billion acre-feet.

Assuming that the average moisture content of this material equals the 25 percent value obtained from the drilling program, the Ogallala Formation currently contains approximately 840 million acre-feet of capillary water; but not all of this water is available for recovery. The formation is composed of sands, gravels, and finer grained materials. These fine-grained materials such as clay and silt hold capillary water tightly, and the capillary water held between these small particles is not available for recovery. Recent work at the University indicates that the formation is between 50 and 70 percent sand, the type of material which is suitable for recovery (Texas Department of Water Resources, 1982). Also, recovery by air requires confining layers that restrict upward air movement, and some of the area may not have such layers in the proper location for the recovery technique.

Also, the Ogallala contains approximately 2.5 billion acre-feet of material that is saturated with water. When the water subject to gravity drainage is removed from this portion of the aquifer, approximately 625 million acre-feet of capillary water may remain.

LITERATURE REVIEW

A significant effort was made to find records of earlier studies and reports that address secondary recovery of ground water. Literature devoted to water was researched first; but after a diligent search, no references were found which appeared to be useful in planning a field research project aimed at the practical recovery of capillary water. Abstracts of 571 articles were prepared.

A search of petroleum-related literature yielded much better results. Secondary recovery of petroleum has been studied and used for more than 60 years. During the period 1920 through 1950, petroleum producers were very active in using air and gas drives. Since 1950, more exotic (and more expensive) means of recovering petroleum have been reported in the literature. Since air is one of the few fluids that can be introduced safely into an aquifer containing potable water, the search focused on the pre-1950 petroleum-related literature.

The study of capillary water has been the subject of numerous laboratory investigations, some of which involved development of theoretical equations to describe the movement of such water. Simplifications made in describing the shape of the soil particles indicate that these studies offer little practical guidance to recovering capillary water.

No project having the primary purpose of recovering capillary water was located in the literature. Some studies that involved movement of capillary water were located. One such involved clearing pathways for petroleum flow and storage of natural gas. Under normal conditions, natural gas was found to displace 10 to 15 percent of capillary water (Popov et al., 1966). In other studies, the use of foam was proven to be more effective in removal of water. Other researchers showed that ammonia gas could remove 81.5 percent of the water; carbon dioxide, 20.8 percent; and nitrogen, 15.5 percent (Eugen'ev and Karimov, 1965).

As a result of the literature search, five potential recovery techniques were identified: air drive, surfactant/foam, thermal, vibration, and electroosmosis. Of these, air drive and surfactant/foam appeared to offer the greatest possibility of being feasible techniques for secondary recovery of ground water, as the other methods are very energy intensive. Subsequent laboratory tests confirmed that only the air-drive method may not be too expensive for economic application.

LABORATORY STUDIES AND MATHEMATICAL MODELS

Laboratory Studies

During the summer of 1981, prior to the official start of the study, the District and the University began early investigation of air drive and surfactant techniques. The goal of the air-drive test was to evaluate the hypothesis that capillary water can be removed by passing air through a formation. A test tank, 5 feet high, 3 feet in diameter and filled with clean sand, was used by University personnel to determine the results of passing air through an unsaturated sand column. Although there were some problems with applying the test results to an actual field operation, they did indicate that significant amounts of water could be recovered. The laboratory test showed that applying 2 pounds per square inch (psi) air-drive pressure resulted in a 20 percent increase in water yield over the amount that drained by gravity alone.

A surfactant is a chemical that reduces the surface tension of water. In effect, it makes water wetter. Surfactants were tested on columns filled with clean sand to determine their impact on drainage. The sand was saturated and allowed to drain. One of the five products used was a common brand of diswashing liquid. The tests showed that use of surfactants increased gravity drainage by as much as one-third. All five products tested showed approximately the same results; increases in drainage occurred as the concentration of surfactant increased, up to a fairly high concentration.

Later, 13 additional surfactants were tested on the sand columns. These 13, plus the five tested earlier, represented all classes of surfactants. The classes are differentiated based on the atomic makeup of the surfactants.

The tests showed that for all chemical surfactants tested, increasing the amount of surfactant in solution increased the amount of drainage until the concentration neared 1:10,000 (1 part surfactant to 10,000 parts water). For some compounds, increasing the concentration above 1:10,000 did not result in increased drainage; for other compounds, at a high concentration of 1:1,000, the range of increase in drainage was from about 4 percent to about 14 percent. At a very high concentration of 1:10, some compounds resulted in one-third more drainage.

Additional laboratory tests were made to evaluate adsorption of surfactants by formation samples taken from the Ogallala. Using formation samples from the Slaton, Texas, drilling site, two surfactants were tested. Testing of several core samples showed that from 28 to 82 percent of the surfactant was adsorbed. Converting these losses to other units indicates that the weight of surfactant adsorbed (lost) would be 2.8 to 8.2 percent of the weight of soil flushed.

Another set of laboratory tests was made to determine whether selected surfactants would increase recovery over that obtained by air injection. First, 12 tests were run on a column of Ogallala material using tap water without surfactant and then two were run with surfactant added to the water. The use of surfactants resulted in no increase in recovery.

An economic analysis of surfactants was made. Based on the low adsorption rate (2.8 percent of soil weight) and assuming a high rate of recovery (25 percent increase in drained water), about 6,000 pounds of surfactant would be required to recover 1 acre-foot of water. A relatively inexpensive surfactant costs $0.50 per pound, resulting in a cost of about $3,000 per acre-foot of water recovered.

Mathematical Models

Mathematical models are used to interpret observed data, to study basic theory, and to predict behavior of a system. A model may be very simple, requiring no more than a calculator to obtain a solution, or it may be quite complex, with the solution requiring the use of a large computer. However, results of any model study are not valid unless the model accurately represents the physical system.

Four types of models were developed and used during this study. Early in the study, two simple models were used to simulate movement of water in the saturated zone as air pressure was applied at an injection well. However, these models were not designed to simulate any increase in saturated storage due to recovered water.

Two other models were used to portray the recovery of capillary water by modeling air and water movement at the same time. One is a complex, sophisticated model, developed by the University's Mathematics Department. It allows for different conditions in the formation and assumes that air is continuous with the atmosphere and that all capillary water is continuous with the water in the saturated zone. This model was applied to a field air-injection test at Slaton, Texas, and some of the model results did not agree well with the rather limited data measured during this test. The model did show that as the formation reached equilibrium, conditions ceased to change appreciably. This led to the development of a steady-state or equilibrium model that was easier, and less costly, to operate. The latter also assumed that all capillary water was continuous with the water in the saturated portion of the aquifer.

This steady-state model was applied to two air-injection test sites at Slaton. It suggested that the confining layer allowed easy air movement, a fact supported by later laboratory analysis. The model analysis showed that the confining layer should have vertical permeability (ability to allow air to pass vertically) of at least three orders of magnitude less than the horizontal permeability of the unsaturated zone if significant yields are to be obtained.

The two above discussed models that attempt to model recovery of capillary water fail to accurately represent the bulk of the capillary water in storage. They assume that all capillary water is in contact with the water in the saturated zone, but as will be discussed later, most of the capillary water is isolated from this saturated zone. These models do accurately represent water and air in the capillary fringe, which is the thin, intermediate zone situated immediately above the water table.

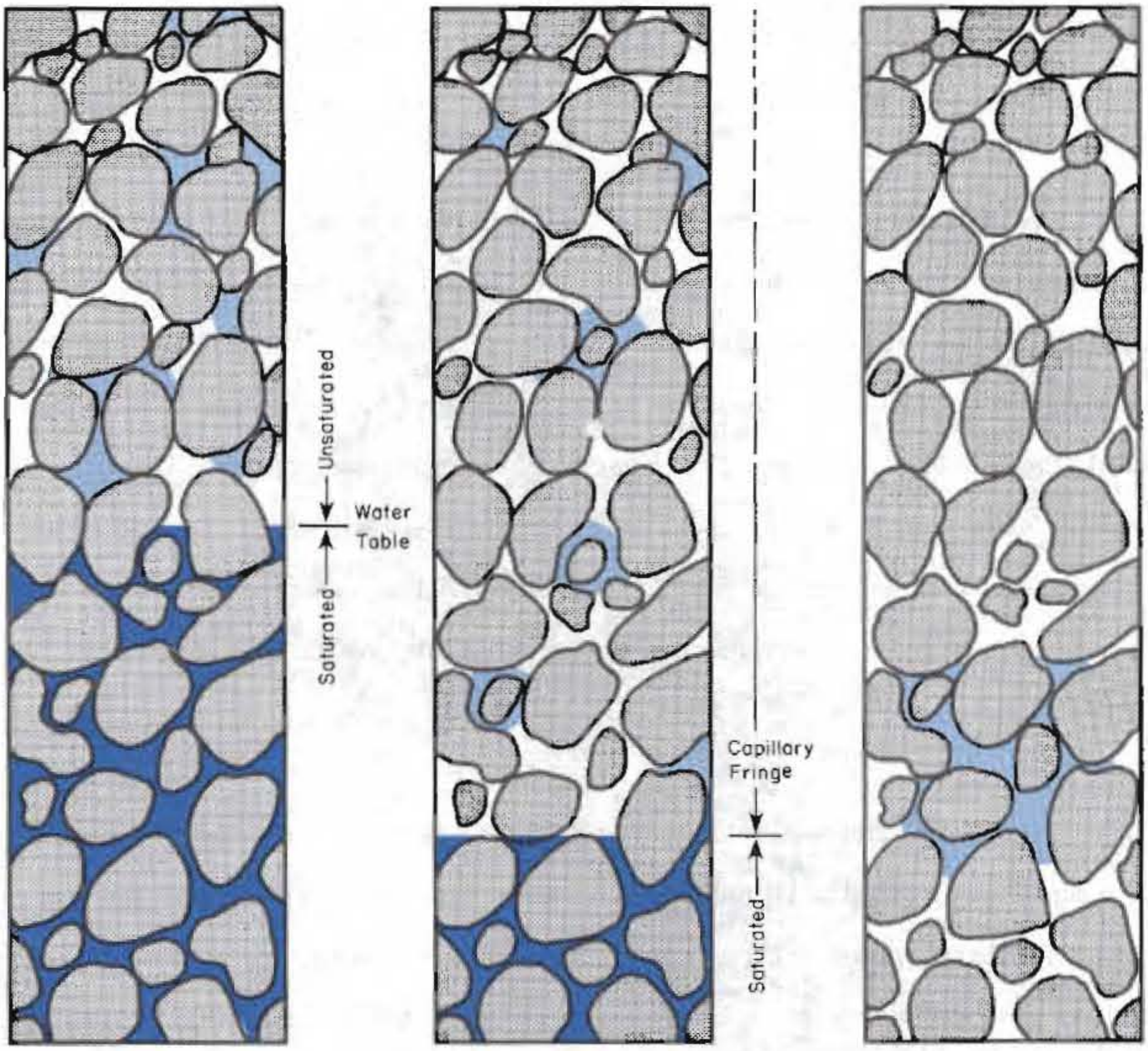
THEORY OF AIR INJECTION INTO THE UNSATURATED ZONE

For most of the Ogallala area, water-level declines of more than 50 feet have occurred since pumping began 40 years ago. It is important to understand how this lowering of the water table affects the amount and distribution of water stored above the water table.

Figure 4a shows a portion of the Ogallala with equal amounts unsaturated and saturated. The water table is about in the middle of the section. Some of the water in the unsaturated zone above the water table is still in contact with the water table. That portion of the aquifer that contains such water is called the capillary fringe. This capillary fringe always exists immediately above the water table and follows it as it moves up and down. The water in the unsaturated zone that is not in contact with the water table and is held in place by surface tension forces is the capillary water that was the focus of this study.

In Figure 4b, the water table has lowered. Some of the voids that were once completely filled with water now contain both air and trapped water. In the capillary fringe of the unsaturated portion, shown in Figure 4b, the water content decreases as height above the water table increases. Within a pore, the strength of surface tension forces increases as surface area decreases. As the height above the water table increases, the force that is needed to keep this water above the water table also increases, meaning that only the smallest voids are able to hold the water.

As the water table continues to fall, the water at the top of the capillary fringe is so high above the water table that surface tension cannot



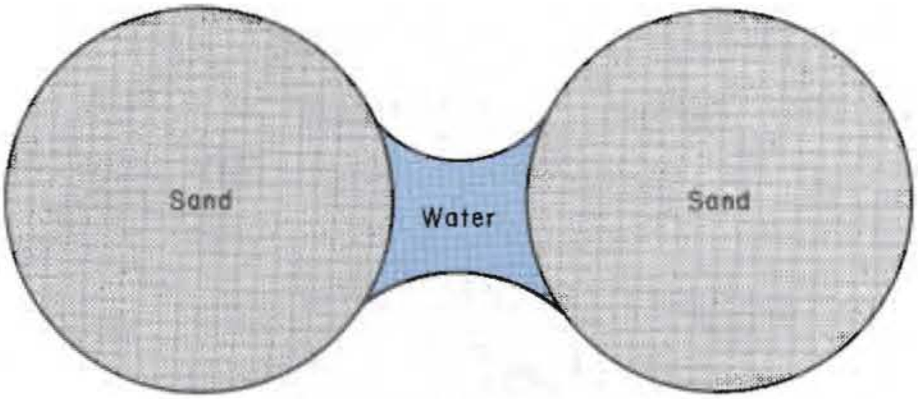
a. Before drainage b. After drainage c. Isolated water

Figure 4
Conceptual Illustration of Effects of Drainage on Water Held in Storage

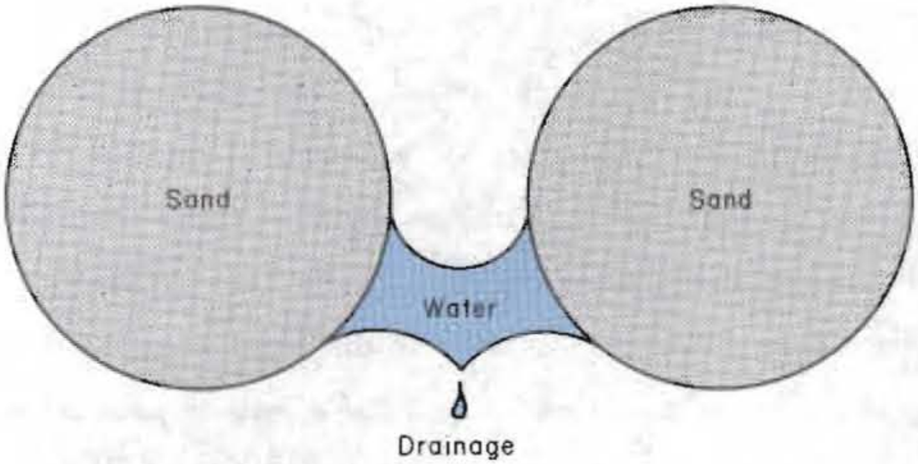
hold the water up, and a separation occurs. Some of the water in the fringe then drains toward the water table, but some becomes isolated and suspended above the water table. Figure 4c illustrates a portion of the Ogallala and shows some of this suspended water. This suspended capillary water is not affected by continued lowering of the water table. Most of the capillary water in storage in the Ogallala is of this type.

Three distinct zones occur within the Ogallala. In the lower zone, the voids are completely filled with water, and saturation is at 100 percent. Water in any one void is continuous with water in other voids. The middle zone, the capillary fringe, is characterized by some voids filled with water and others filled with air. Saturation is less than 100 percent and decreases with height above the water table. Water in any void filled with water is continuous with water in the saturated zone, and air in any void is continuous with the atmosphere. The highest zone is the unsaturated portion of the aquifer that is above the capillary fringe. The degree of saturation is not affected by height above the water table. Air is continuous with the atmosphere, but any water held between sand grains is not continuous with the water table. Recovery of water from this highest zone (isolated water zone) was the focus of the study.

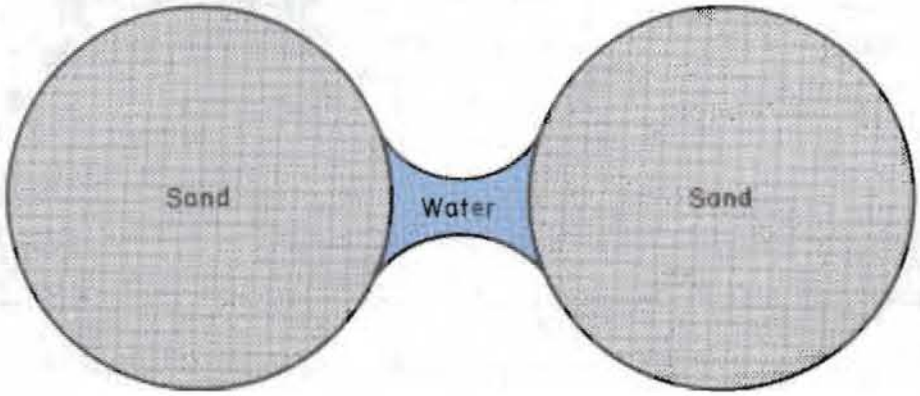
The air-injection recovery theory may be explained by assuming that the sand grains are round. This condition rarely occurs in nature, but the assumption allows the application of mathematics to the problem. Figure 5a shows two sand grains that almost touch. Some capillary water is trapped between the grains. The surface tension force acting in the top water surface tries to pull the water up, and the tension in the bottom water surface and gravity pull the water down. For the water to remain between the grains, the



a. Equilibrium before air injection, uniform air pressure



b. Reaction to increased air pressure on top



c. Equilibrium after some water removal, increased air pressure on top

Figure 5
Idealized Capillary Water Conditions

force acting up, the tension in the top surface, must equal the downward force, the tension in the bottom surface plus gravity.

Assume that air is being injected into the formation from the top. Since the top of the water surface is closer to the injection air source, the air pressure on that surface is greater than the air pressure on the bottom water surface. The water reacts to this imbalance of forces by moving downward. If the pressure imbalance is small, the water may reach a new equilibrium in that the forces acting down (air pressure on top surface, weight of water, and surface tension in the bottom water surface) equal the forces acting up (air pressure on bottom surface and surface tension in the top water surface).

If the air pressure difference is sufficiently large, the water will be pushed down so far that the surface tension in the bottom water surface cannot hold the water, and it will drain (Figure 5b). After some water has drained, that remaining may return to a new equilibrium condition (Figure 5c). This means that with the same pressure difference, drainage will occur at one moisture content, but not at a lower moisture content. The difference in pressure would have to be increased to cause additional drainage. If the pressure differential can be made sufficiently large, it is possible to force out almost all of the capillary water between the sand grains.

Based on the above relationships, it can be assumed that if the grains are large and the amount of water held between the grains is large (degree of saturation is high), drainage can occur with small pressure differences. If either the grain size or degree of saturation is small, a larger pressure difference is needed to cause drainage.

The sequence of events that will occur as secondary recovery takes place by air injection is shown in Figure 6. As air pressure builds in the formation near the injection well, water begins to drain from voids. The drainage tends downward due to gravity, so the lower sand grains soon become wetter and wetter until they become saturated. Also, as the voids contain more and more water, they contain less air, and this results in slower air movement. Water can move downward comparatively rapidly under saturated conditions. The upper voids contain less water; thus, they have less resistance to airflow, and the air moves outward more rapidly from the injection well through them. The result is that the lines representing equal pressure resemble an upside-down bell. The movement of the water is downward (due to gravity) and outward (carried along with the air). Eventually, a mound of water would grow underneath the injection well; the water table would rise. Additional water would be available to wells due to the induced movement of capillary water to the water table.

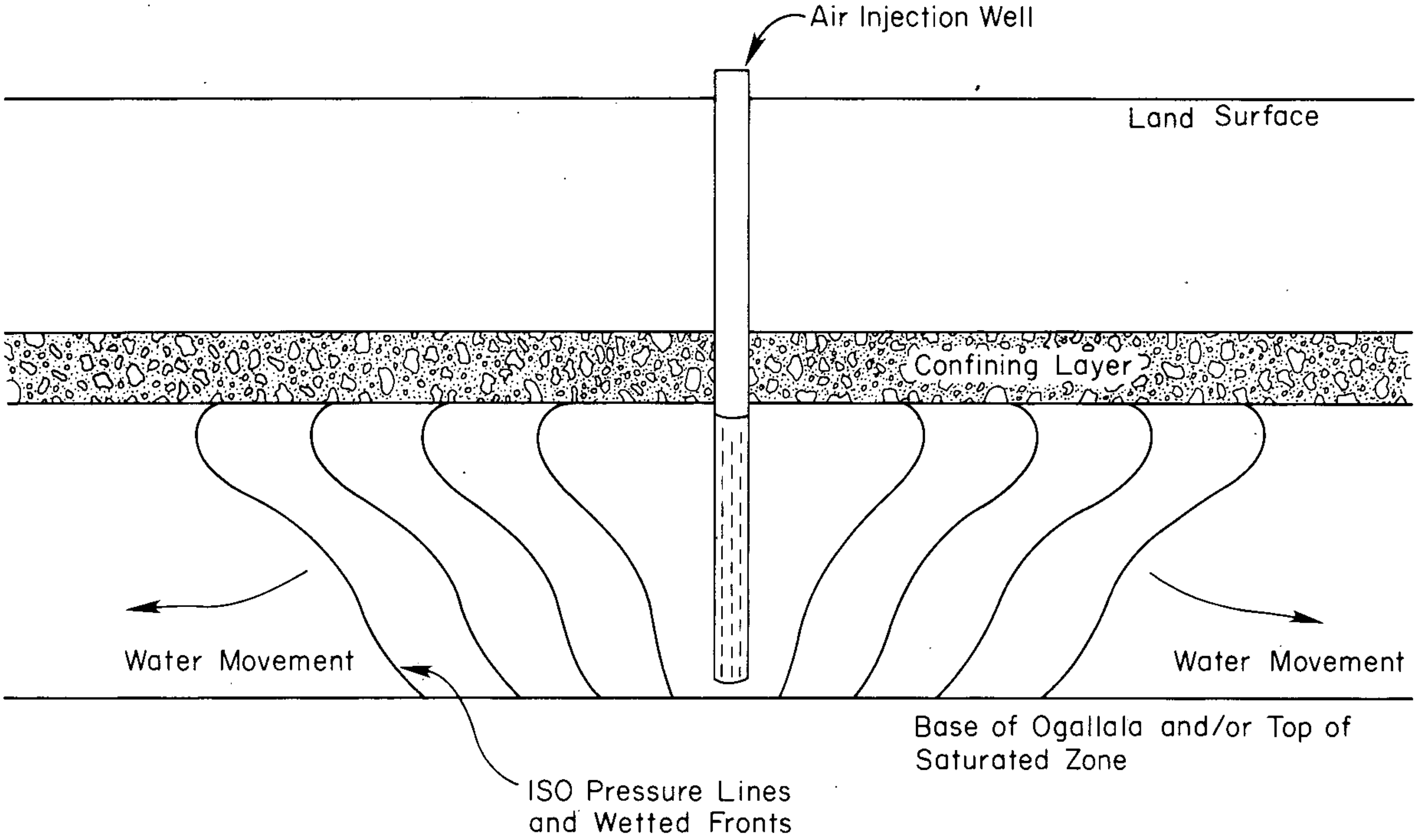


Figure 6

Conceptual Illustration of Air Injection Theory

FIELD-TEST PROGRAMS

Two of the study objectives involved field testing of secondary recovery techniques. Based on the preliminary laboratory results which showed that additional water could be obtained by air injection and the literature review which indicated that air injection could free capillary water, a field program was operated concurrently with other phases of the work. This was necessary in part because of the scheduled short duration of the study and the need to conduct field tests in unison with area crop irrigation patterns.

Three field programs were conducted. Two were performed at a site near Slaton, Texas, and one near Idalou, Texas. See Figure 7 for the site locations.

Slaton Air-Injection Test One

Early in the study, many unknowns existed. Little was known about how air injection could be accomplished and how a test site could be monitored to determine the results of the test. To attempt to learn more about some of the unknowns before making large expenditures, it was decided to perform a small-scale air-injection program.

The objectives of this test were to:

1) Evaluate physical air-injection mechanisms and well designs,

2) Evaluate type and spacing of monitoring equipment,

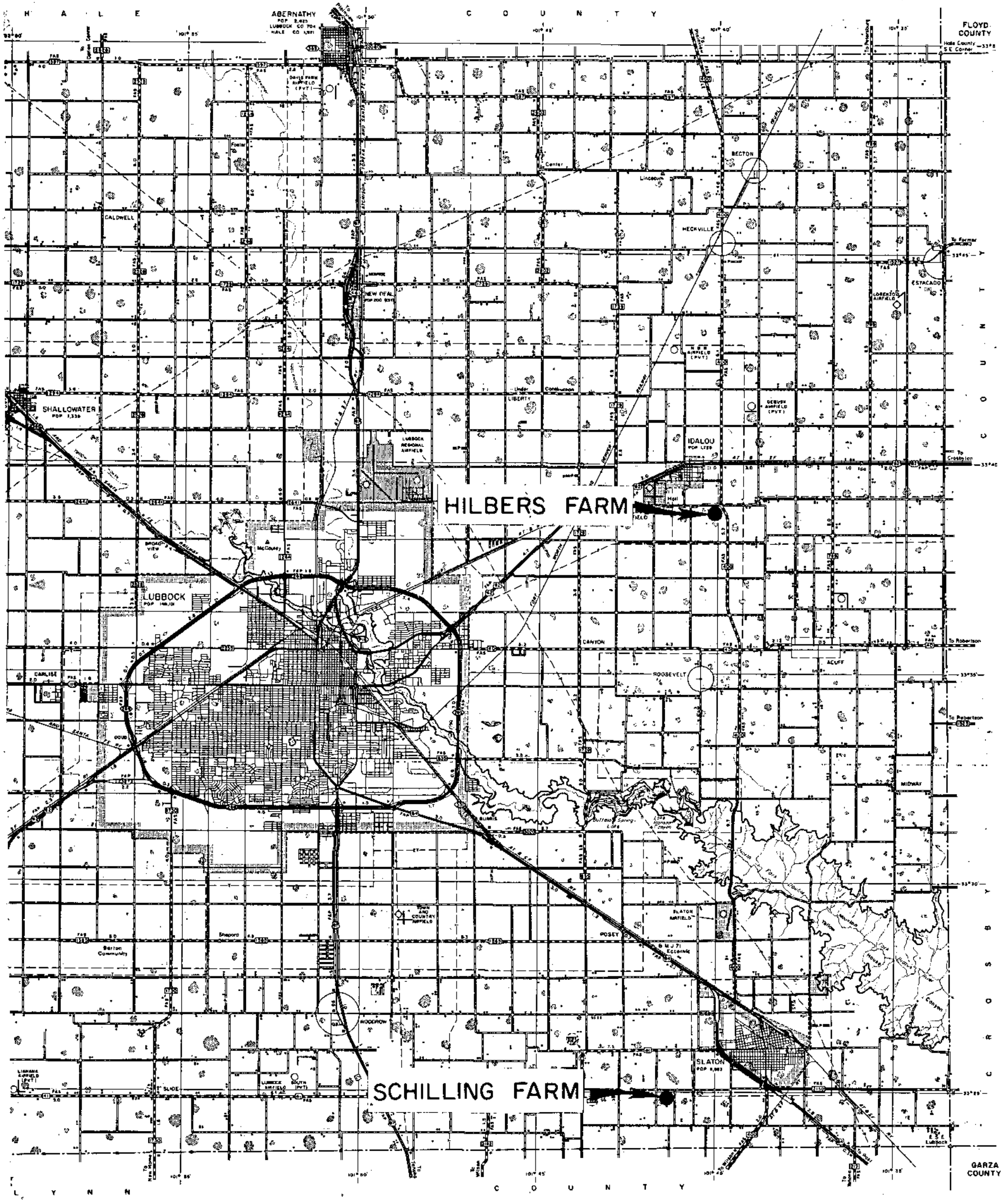


Figure 7
Location of Field Program Sites

3) Evaluate responses of unsaturated and saturated zones to air pressures,

4) Evaluate, qualitatively, whether capillary water can be released, and

5) Develop design criteria for installation of a large-scale air-injection field program.

The test site had to be close to Lubbock and had to have some type of confining layer present above the water table. The confining layer was necessary so that the unsaturated section could be pressured with air. Without such a layer, air would escape rapidly to the atmosphere.

A site which appeared to satisfy the requirements was located near Slaton, Texas, on Mr. Ronald Schilling's farm. The Department drilled a soil moisture test hole on this property, and a hard, rock layer, between 11 and 16 feet thick, was found to occur about 50 feet above the water table.

This first test of an air-injection program involved design and installation of seven wells: one for air injection, five for air-pressure monitoring, and one for water-level monitoring. The air-monitoring wells were designed to permit the measuring of air pressure at different depths representing different layers in the formation. The water-level monitoring well and two nearby irrigation wells were equipped with continuous water-level recorders to record changes in the water table.

The well construction techniques used were designed to prevent air leakage. Steel casings were cemented through the rock layer. Well logging techniques were used to accurately locate suitable positions for air-monitoring intake devices. Construction techniques were satisfactory except for repeated failures of attempts to install tubes to monitor changes in soil moisture.

The air-injection well was constructed by drilling a 12 ¼-inch diameter hole from the surface through the rock layer to a depth of 69 feet. A 6 5/8-inch diameter steel casing was then cemented in place. A 5 9/10-inch diameter hole was then drilled from 69 feet to a total depth of 116 feet, and 50 feet of 5-inch diameter mill slot casing was set in the lower hole. The lower casing had 5 percent open area and was not plugged at the bottom. The water level in the well was about 121 feet below the land surface. The target injection zone was from the bottom of the rock layer to the water table, a distance of about 50 feet. This zone contained gravel embedded in coarse-grained sand.

Knowledge of how moisture content changes is a key factor in evaluating the success of secondary recovery techniques. Moisture content is measured by using an electronic device that is lowered into the formation. The device uses neutrons to determine soil moisture. It must be used inside a 2-inch diameter aluminum tube, and the tube must be in contact with the soil. After repeated attempts to install the soil-moisture tubes using various hole construction techniques, all of which ended in failure, installation of the tubes was abandoned for this first test.

The test facilities were constructed during the period December 1, 1981, through January 20, 1982. The cost of drilling and materials totaled about $20,000, not counting one-half man-year of effort by District staff.

Prior to beginning air injection, data were collected at the site on barometric pressure, air pressures in the formation, water levels, and soil moisture. This monitoring began 7 days prior to the start of air injection.

The air-injection test started just before noon on January 23, 1982, and continued for 9 days, ending at noon on February 1, 1982. Except for short shutdowns to maintain the compressors, air injection was continuous. For the first 21.5 hours, the air-injection rate was 660 cubic feet per minute (cfm) with a pressure in the air-injection well of 10 psi. For the remainder of the test, the rate was 1,000 cfm with a resulting well pressure of 12 psi. An estimated 12.69 million cubic feet of air was injected during the test.

The formation reacted rapidly to the injected air as the air pressure built up, and water levels changed. Air pressure in a zone 106 feet below the surface and 101 feet south of the air-injection well showed immediate response to air injection. Soon after the test started, the pressure stabilized at about 1.4 psi for an injection rate of 660 cfm. Within about 5 hours of the increase in injection rate to 1,000 cfm, the pressure had stabilized at about 2 psi. Pressure tended to increase during the rest of the test, reaching 2.18 psi at the end. The pressure also reacted rapidly to compressor shutdowns. At final shutdown, the pressure returned to near atmospheric within 13 hours.

At the start of the test, an almost immediate water-level rise occurred in the newly constructed water-level monitoring well located 160 feet from the air-injection well. About 36 hours after the test began, the water-level rise equaled 7.5 feet. It then tended to drop slowly until the end of the test. Just prior to the end of the test, the residual net rise was slightly above 5 feet. After the test ended, the water level dropped rapidly, eventually showing a net loss of 2 feet. However, it soon began to rise again and finally approached the value it had at the beginning of the test. The water levels in the two irrigation wells also showed rises during the test, but both rose less than 2 feet. After the test, these water levels tended to drop, but much slower than in the other well.

The large, rapid fluctuations shown in the water level in the new well must, in large part, be due to pressurizing of the formation. Only a small amount of the measured changes could be caused by movement of water in the saturated zone, and the change was too rapid to be caused by capillary water reaching the water table. Model studies showed that probably a large portion of the water in the saturated zone beneath the air-injection well was forced outward due to the air pressure. Some of the decline after the test is probably due to the refilling of this depression in the water table.

Water levels in the two irrigation wells stayed above their pre-test levels for about 7.6 days. After this time, they began to fluctuate around the pre-test level. Daily fluctuations due to barometric pressure differences are significant at this site. Water-level changes of as much as 1 foot were noted prior to the test. It is possible, however, that the lingering rise in water level was due in part to recovery of capillary water.

Several weeks after this test, the Department obtained core samples from the unsaturated zone near the test site. Samples were taken at two locations, 152 and 300 feet, respectively, from the air-injection location. The average moisture content of the core samples was 14.1 percent. Earlier, the

Department had obtained cores from a site approximately one-half mile from the air-injection well. Average moisture content of samples from that site was 29.6 percent. If the earlier obtained data were representative of conditions at the air-injection site, the difference in moisture content would be about 15 percent by volume, representing a moisture reduction of about 50 percent in the unsaturated zone after air injection.

Thirty days after the injection test ended, the three water-level monitoring wells showed increased water levels of between 0.5 foot and 2 feet. Although the wells are significantly influenced by barometric pressure changes, the water levels did appear to be higher. If these rises are representative of the area, the increase in water in storage would equal about 7 acre-feet. The actual existence and source of this additional water is in doubt, however.

The Slaton test one field program met its objectives. The air-injection well worked, and the air-monitoring equipment performed as expected. The rapid change in water level was unexpected and not clearly understood. The well designs were good, but quality control must be rigidly maintained. The design of water-level monitoring wells was found to need slight change. The absence of moisture-monitoring data showed that it is very important to obtain this information.

Slaton Air-Injection Test Two

The test one program provided valuable information on how to conduct a field test. The design of several items was changed, and it was decided to test these changes at the Slaton location prior to conducting a large-scale field test.

One major change was the conversion of the water-level monitoring well from one exposed to the atmosphere to one that was pressurized. The recorder was enclosed in a pressure tank so that any changes in the formation air pressure alone would not cause a change in the recorded water level. Additional air monitors were installed to obtain air pressure readings for different layers in the formation.

During test one, air had been injected through a 5-inch diameter mill slot casing. For the second test, the casing was removed and the hole filled with 1- to 1½-inch diameter gravel. Tests at the University showed that such a gravel pack would be very efficient in distributing air into the formation.

Additional attempts were made to install soil moisture meter access tubes. All efforts to obtain a skin-tight fit with the aluminum tubes failed. Eventually, a larger, 4-inch diameter hole was drilled and the tube installed. The annulus between the aluminum tube and the borehole was filled with wet sand. Frequent monitoring through two such tubes showed that eventually the moisture reading ceased to change, meaning the sand reached equillibrium with the formation. Although such construction with introduced sand fill may result in readings that do not correctly show the absolute amount of moisture in the formation, it is felt that, after a period of stabilization, the readings would accurately show moisture content changes that would occur during the test. Installation of gypsum blocks was also attempted as a means of determining changes in soil moisture. These blocks failed to show changes in moisture, and this technique was abandoned.

Fifteen wells were used in the second test, including one for air injection, three for moisture monitoring, five for air monitoring, and six for water-level monitoring. Air injection began about 5:30 p. m. on May 28, 1982, and ended about 10:00 a. m. on June 1, 1982. The initial injection rate was 850 cfm. It was increased to 1,700 cfm at 5:20 p. m. on May 29, 1982, and later increased to 2,100 cfm at 10:30 a. m. on May 31, 1982. Injection pressure reached 180 psi at the well head, but only 15.8 psi 30 feet into the gravel pack. During the 3½-day test, 8.5 million cubic feet of air was injected.

The air-pressure monitoring wells showed that the pressure in the formation responded rapidly to changes in air injection. Pressure at the monitor located 101 feet from the injection well reached a maximum of 4.5 psi. The monitoring showed that there was no vertical difference in pressure.

Soil-moisture measurements made in the access tubes generally showed virtually no net change in moisture content. Data from one tube may indicate a slight net lowering of moisture content. The readings from the access tubes agree well with the moisture values obtained from cores the Department obtained after the first test at Slaton.

Water levels reacted rapidly to the air injection. The water level in a well some 16 feet from the injection well fell rapidly during the test, an indication of the dewatering of the saturated portion of the aquifer under and near the injection well. Water levels in other wells showed rapid rises during injection (as much as 2.7 feet), and equally rapid declines immediately after injection stopped. The rapid rise was again due in large part to pressures applied to the aquifer. The rapid decline was in large part due to refilling of the dewatered section under the injection well. Two wells showed increased water levels for as long as 6 days after the test ended. This could be due to recovered capillary water. One well located three-fourths of a mile from the injection well showed a water-level rise that began prior to and continued through and after the test. This rise was due to the well's recovery after being pumped. Several irrigation wells in the area were pumped within 4 weeks of the start of the second test at Slaton. Based on the measurements of four wells that were not pumped, it could be calculated that the aquifer's storage was increased by 7 acre-feet. However, the water-level rises soon vanished, leaving the existence and source of this water in question.

This second test at Slaton accomplished its objectives. Monitoring techniques were greatly improved over the first test. The gravel pack injection well was highly inefficient, but the sand-packed moisture tubes appeared to work adequately. The pressurized water-level recorders were an improvement.

Idalou Field Program

Results of the two tests at Slaton indicated that a large-scale field test was needed. The principal objective of such a test would be to demonstrate the technical and economic feasibility of using air injection as a method of secondary recovery of capillary water. Again, the two primary requirements for the test site were that a confining layer be present and that it be located near Lubbock where materials, supplies, and personnel were most conveniently available.

A site near Idalou, Texas, on the farm of Mr. Clifford Hilbers was selected. The site is underlain by layers of clay varying in thickness from 2 to 12 feet. One clay layer is so restrictive that a saturated zone occurs above the water table. The clay prevents the water from draining by gravity to the water table. This is in contrast to the Slaton site that was underlain by a hard layer of rock.

The Idalou program involved the design and construction of 17 wells. These included (a) one air-injection well, (b) seven air-monitoring wells, (c) five soil-moisture tubes, and (d) four water-level monitoring wells. Figure 8 shows a view of the air-injection well together with associated air compressors and pressure-monitoring equipment. The bottom of the lowest clay layer was about 144 feet below land surface with the water table being about 161 feet below land surface. The target air-injection zone contained fine-grained sand about 18 feet thick.

Well construction techniques made use of the information gained at the Slaton site. The air-injection well was 180 feet deep with 30 feet of Johnson Irrigator brand of wrapped well screen set in the lower portion of the hole. The air-monitoring wells were constructed to permit the measurement of air pressure in various depth zones and at various places around the site. The soil moisture access tubes were installed to a depth of 180 feet using the sand-pack method. The water-level monitoring wells were drilled through the saturated portion of the aquifer and equipped with a pressurized, continuous water-level recorder (Figure 9). Construction required 30 working days and cost over $60,000.

As with the earlier tests, pre-test data were collected at the site on air pressures, water levels, and soil moisture; Figure 10 shows some of

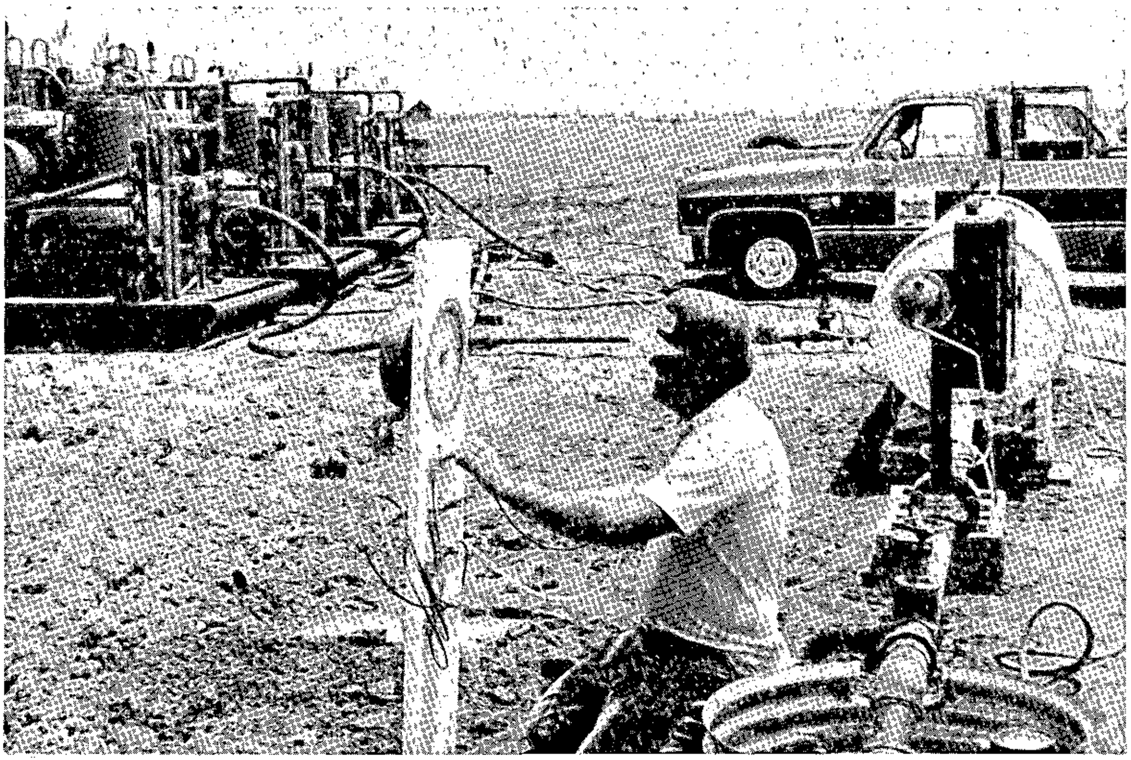


Figure 8
Idalou Field Test Site, Showing Air-Injection Well (foreground), Air Monitoring Equipment, and Air Compressors

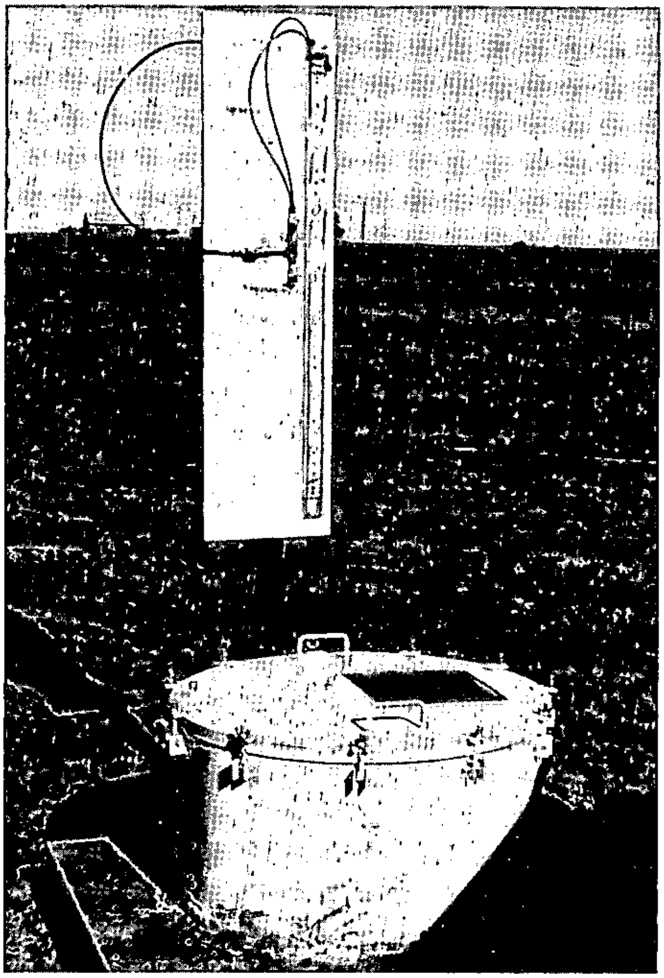
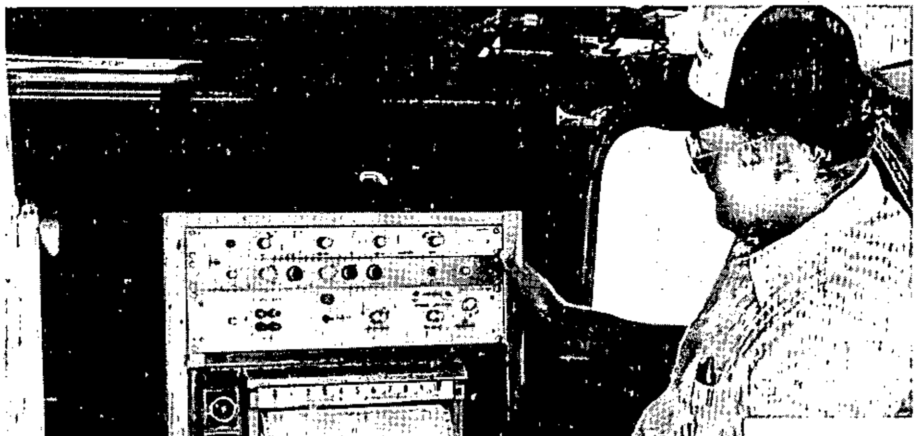
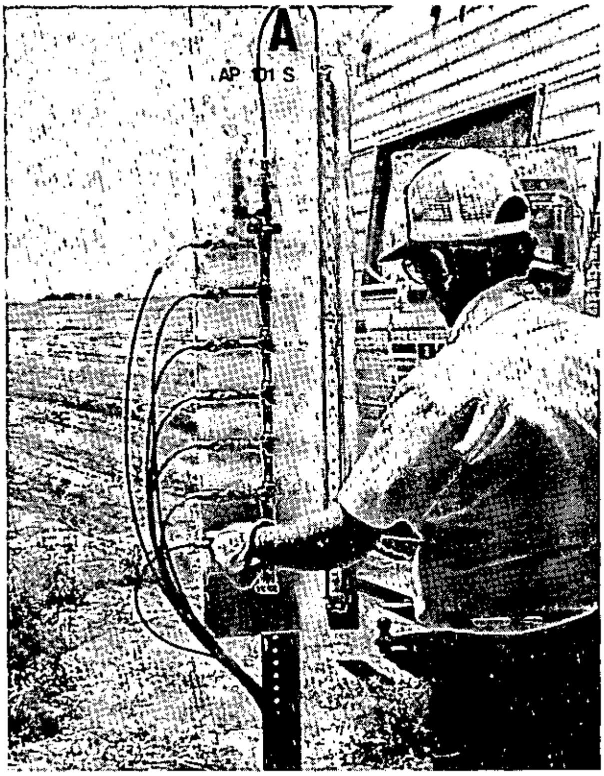


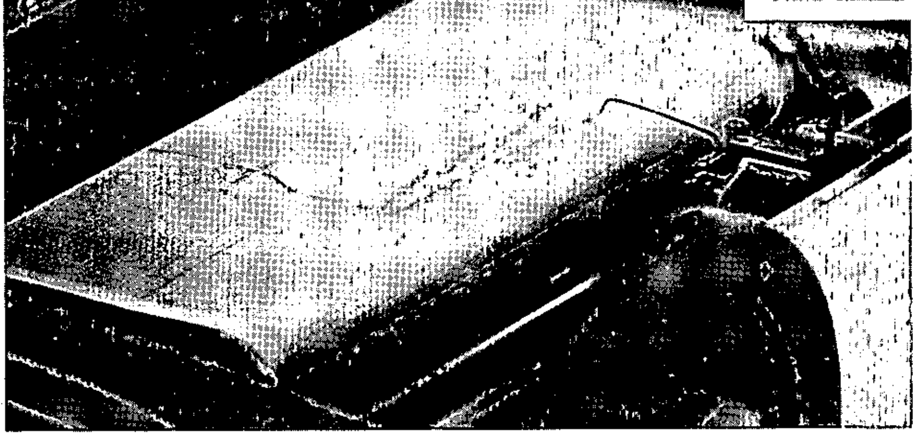
Figure 9
Pressure Tank Containing Continuous
Water-Level Recorder



Continuous Measuring of Soil Moisture



Recording Air Pressure Measurements



Water Level Recorder Showing Rapid Rise in Water Level

Figure 10

Field Test Monitoring Techniques

the techniques used. Water levels showed cyclic fluctuations which may have been caused by barometric pressure changes, moon tide, or some other phenomenon. Moisture readings showed that, in the upper portion of the target zone, the soil-moisture content was around 22 percent. In the lower portion, it was around 30 percent. The capillary fringe appeared to extend about 5 feet above the water table.

The Idalou air-injection test started just before 1:00 p. m. on June 17, 1982. Air was injected for almost 143 hours, slightly less than 6 days. Injection stopped at about 11:30 a. m. on June 23, 1982.

The initial air-injection rate was 250 cfm with a pressure of 27 psi in the injection well. Within 10 minutes of start-up, water, air, and mud was ejected from a moisture-measurement tube located 20 feet from the injection well. About 7 hours into the test, the injection rate was increased to 900 cfm with a resulting pressure of 100 psi. This rate was maintained for 72 hours. During this period, water flowed at the surface in water-level monitoring wells located 50 and 125 feet from the injection well. These wells and the moisture-measurement tube were then capped. Subsequently, water and air also began to flow upward around the tube located 110 feet from the injection well. These failures were due to the high pressures forcing water away from the injection well. This water formed a wave that was prevented from moving higher by the clay layers. This resulted in creating artificial artesian conditions that forced water to the surface (Figure 11).

At 5:00 p. m. on June 20, 1982, the injection rate was increased to 1,250 cfm with a resulting pressure of 122 psi. Within about 24 hours, the pressures in the formation ceased to change significantly, and at 4:00 p. m.

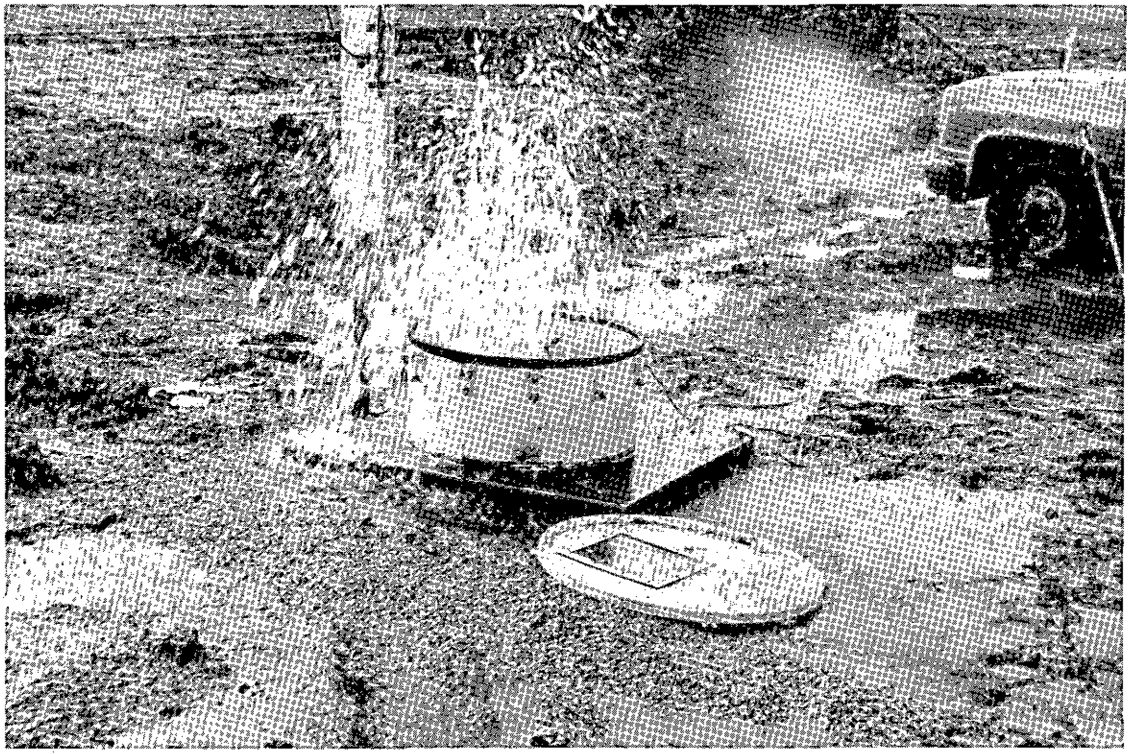


Figure 11

Water Forced to Surface During Idalou Field Test on June 21, 1982, the rate was increased to 1,750 cfm with a pressure of 142 psi. At 11:00 a. m. on June 22, 1982, the injection rate increased to between 2,200 and 2,300 cfm, the maximum rate of the compressors. The injection pressure was 160 psi. During the entire test, over 10 million cubic feet of air was injected.

Formation pressures during this test were much higher than those observed during the two previous tests. Pressure at the Idalou site measured 160 psi, more than five times the 30 psi measured at the Slaton site. This high pressure was due in large part to the type of material in the target zone. The fine-grained sand at Idalou restricted air flow much more than did the coarse sand and gravel at the Slaton site. Also, the clay layers proved a better confining layer than did the rock at Slaton. The high pressures undoubtedly led to the previously discussed failures of some of the monitoring wells.

As in the earlier Slaton tests, air pressure in the formation reacted rapidly to changes in air-injection rate. Within 10 hours of injection, increased air pressure was detected 70 feet from the injection well. In 24 hours, a pressure increase was detected 140 feet away, and in 3 days, 330 feet away. Maximum pressure 330 feet from the injection well was over 36 psi. Based on a statistical analysis of the data obtained from all air monitors, it was calculated that the air-pressure front in the target zone extended as far as 1,400 feet from the injection well. This analysis involved significant extrapolation since the most distant air pressure monitored was 330 feet, but the measurements at the distant monitors could not be used to prove or disprove the passing of the pressure front.

The only one of the five soil-moisture tubes that could be used was located 297 feet from the injection well. Moisture measurements were made frequently in this tube using two types of instruments. In the upper portion of the target zone, the moisture content was less following the air injection test. The lower section contained more moisture due in part to its being saturated because of the rise in the water table caused by the applied pressure.

Eleven inches of rain fell on the site immediately before and during the test. After the test, soil samples taken at 10-foot depths at three locations near the site contained insufficient moisture to allow rapid drainage. Soil-moisture measurements made in two of the soil-sample holes using the neutron moisture meter also showed relatively low moisture levels. It is unlikely that the heavy rains recharged the Ogallala at the test site.

As in the other tests, the water table reacted rapidly to changes in air injection. The saturated section was dewatered near the injection well. This dewatered area probably extended 300 feet from the well, and the water table was depressed more than 100 feet beneath the injection well. Water that was forced from this dewatered zone was pushed outward from the injection well in a fashion similar to a wave in a lake. When the test was over, much of this water returned to the dewatered portion of the formation. Several wells showed sharp rises during the test (an example is shown in Figure 10) and sharp declines after the test. Much of this change was due to the pressure applied at the injection well. Wells near the injection well showed net declines 1 month after the test. Again, this probably is due to slow filling of the dewatered portion of the formation. The water level in one well that probably was subjected to the increased air pressure and that was located over 800 feet from the injection well, showed the rise and fall, with the lowest water level measured being almost 2 feet above the pre-test level. That level occurred more than a week after injection stopped, and the water level continued to rise, with a gain of over 3 feet after 3 weeks. Several wells located beyond the area subjected to air pressure showed rises of over 2.5 feet 3 weeks after the test. These water-level rises could be the result of recovery of capillary water, but other causes for the increases are also possible.

Using all data obtained at the Idalou site, net-change-in-storage calculations were made. Thirty days after the test, the indicated net increase in storage for the region within 2,800 feet of the injection well (total area of 565 acres) was 225 acre-feet.

Water levels were measured in wells near the site 100 days after the end of the test. Almost all of the wells showed rises even though some of them were pumped after the test. Estimated pumpage was 60 acre-feet. Wells near the injection well had water-level rises between 1.75 and 2.0 feet. A well located one-third mile north of the injection well had over one-third foot rise, but this well was the hardest pumped well. Three wells located between three-tenths and five-eighths mile southwest of the injection well showed rises of 4.18, 5.54, and 5.58 feet. An additional 315 acre-feet more water was indicated in storage 100 days after the test. Most of the increase in storage is southwest of the injection well and is beyond the area believed to have been subjected to air pressure.

It is impossible to determine for certain what portion of these volumes may be recovered capillary water, but it is certain that the long-term trend for the Ogallala is to lose, not gain, storage.

ECONOMIC ANALYSIS

One of the key factors of this study was the requirement that any recovery technique implemented must be economically feasible. Consequently, an analysis was made to estimate the economical feasibility of the recovery technique tested during the Idalou field program.

The cost of a recovery program is a key factor in the analysis. Based on the experience obtained at Idalou, costs for constructing a similar air injection well and conducting the injection for 7 days were estimated. Costs for monitoring were not included. The costs estimated were as follows:

Construction of air injection well	$ 4,880.50
Compressor rental with operator	3,620.20
Fuel for compressor	7,408.28
Labor	3,000.00
Total	$18,908.98

The estimated increase in storage at the Idalou site was about 225 acre-feet. If all of this water was recovered capillary water, the cost of its recovery would be about $84.00 per acre-foot.

The direct benefit to agriculture of having capillary water made available for pumping was evaluated by studying the yield of cotton grown under irrigation versus that grown under dryland conditions. The analysis considered two management levels (average and high, with respective average yields of 400 and 500 pounds of lint per acre), three cotton prices ($0.55, $0.65, and $0.75 per pound), three costs of energy ($3.50, $4.00, and $4.50

per MCF of natural gas), three pumping efficiencies (70, 62, and 54 percent), and four pumping lifts (100, 150, 200, and 250 feet). The analysis showed that with average management, the price of cotton would have to be $0.65 per pound for the value of the irrigated cotton to exceed that of dryland cotton. With an average crop yield, a farmer could pay no more than $25.00 per acre-foot for the additional water if the pumping lift was shallow (100 feet), pumping efficiency was high (72 percent), energy was cheap ($3.50 per MCF of natural gas), and the price of cotton was high ($0.75 per pound). For the best of conditions (high yield, high cotton price, high pumping efficiency, low pumping lift, and low energy costs), the farmer could pay about $88.00 per acre-foot, and recovery of capillary water would be marginally profitable. Of course, crops other than cotton can be grown and some of those may show a higher value for water.

The direct benefit of having additional water available for municipal and industrial use was evaluated by studying the City of Lubbock water system. The study showed that the average cost to the City for ground water was $62.00 per acre-foot. Based on the current rates, the City receives $0.90 per 1,000 gallons. The net return equals $136.00 per acre-foot. This could mean that a municipality could spend $136.00 per acre-foot for the added water, if the water could be produced with in-place equipment. If new production equipment was required, the amount which could be spent on secondary recovery would be less.

The above discussion assumes that the price of water would not rise. Actually, there is almost no limit on the price that a person will pay for drinking water, especially if no other source is available. Currently, many domestic users in Lubbock buy bottled drinking water for $0.93 per gallon, 1,000 times the base rate. Almost any cost of recovering water may be economically feasible if the recovered water is the only water available to drink.

These economic analyses did not consider the availability of current water supplies. If a water producer (farmer or city) has sufficient supplies available without secondary recovery, there is no economic incentive to increase the supply. If the water supply decreases so that it affects the producer, an incentive begins to occur and the recovered water begins to become worth more to the producer. The incentive discussed previously ($84 per acre-foot for irrigated cotton and $136 per acre-foot for municipal use) would apply fully only as the time approaches when the secondarily recovered water is the only water available.

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STUDY TEAM PERSONNEL

The following is a partial list of the people who contributed to the completion of this study. Without the efforts of all involved, the study could not have been accomplished in such a timely and complete fashion.

Texas Department of Water Resources (project sponsor and general assistance): C. R. Baskin, P.E., served as Project Administrator. Other Department staff who contributed significantly to the project were Tommy Knowles, PhD, P.E., Henry Alvarez, Richard Preston, Gene Couch, Gail Duffin, Marion Striegler, P.E., and Lewis Barnes.

High Plains Underground Water Conservation District No. 1 (overall study activities, including field tests): A. Wayne Wyatt, District General Manager, served as Project Manager. Other District staff who contributed significantly to the study were D. D. Smith, Don McReynolds, Burnie O. Goolsby, Mike Rissinger, Jerry Funck, Kenneth Carver, and Kathy Redeker. Donald G. Rauschuber, P.E., worked under contract with the District and deserves much credit for his diligent efforts in completing this study.

Water Resources Center at Texas Tech University (laboratory tests, literature research, and analytical studies): Robert Sweazy, PhD, P.E., served as Project Coordinator for the University. Other University faculty and staff involved with the project were Bill Claborn, PhD, P.E., George Whetstone, PhD, P.E., Heyward Ramsey, PhD, P.E., Lloyd Urban, PhD, P.E., Richard Bartsch, PhD, Duane Crawford, PhD, P.E., Arthur Stoecker, PhD, Richard Zartman, PhD, and Robbin Harris.

Texas A&M Agricultural Experiment Station at Lubbock (laboratory analysis of soil samples): Station work was under the direction of Charles Wendt, PhD, with assistance from Mike Gerst.

Advisory Board (professional advise on techniques, procedures, and evaluations): The Board consisted of Dr. Charles Wendt (Chairman), Dr. Warren W. Wood, Dr. Ron Lacewell, Ron M. Brimhall, and Terry Doherty. Their respective fields of expertise and agency affiliations have been included in the introduction to this report.

ACKNOWLEDGEMENTS

The study team appreciates the cooperation extended by the property owners in the High Plains who supplied information concerning their wells and, in many instances, also allowed access to their property. Thanks are given to the State Department of Highways and Public Transportion for assistance during construction of some of the test holes. Thanks are also given to Messrs. Robert Luker, Ronald Schilling, Edwin Axl, W. L. (Bill) Broadhurst, and Gaston Wells for allowing test holes to be constructed on their property. Special thanks are due Messrs. Ronald Schilling and Clifford Hilbers for allowing their property to be used for field tests.